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Modeling the Black Hole Spin

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Ever since the launch of the NuSTAR mission, the hard X-ray range is being covered to an unprecedented sensitivity. This range encodes the reflection features arising from active galactic nuclei (AGN). Especially, the reflection of the primary radiation off the accretion disk carries the features of the manifestation of General Relativity described by the Kerr metric due to rotating supermassive black holes (SMBHs). We show the results of the broadband analyses of Mrk 876. The spectra exhibit the signature of a Compton hump at energies above 10 keV and a broadened and skewed excess at energies ~6 keV. We establish this spectral excess to be statistically significant at 99.71% (~3 sigma) that is the post-trail probability through Monte Carlo simulations. Based on the spectral fit results and the significance of spectral features the relativistic reflection model is favored over the distant reflection scenario. The excess at ~6 keV has a complex shape that we try to recover along with the Compton hump through a self-consistent X-ray reflection model. This allows inferring an upper limit to the black hole spin of a<0.85, while the inclination angle of the accretion disk results in i=32.84° (+12.228.99) degrees, which is in agreement within the errors with a previous independent measurement (i=15.4° (+12.1/-6.8)). While most spin measurements are biased toward high spin values, the black hole mass of Mrk 876 (2.4x10^8 $M_\odot$ < M < 1.3x10^9 $M_\odot$) lies in a range where moderately spinning SMBHs are expected.

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1. Introduction

In the unified view of active galactic nuclei (AGNs), the primary radiation is emitted by the hot corona surrounding the supermassive black hole (SMBH). This is seen as a power-law spectrum by an observer. This primary radiation also irradiates the accretion disk that reflects it through several reprocessing steps, which include the electron scattered broad Compton hump above 10 keV and the fluorescence emission of K α of most abundant element. Most emission lines are unresolved at low X-ray energies resulting in the so-called soft X-ray excess below ~1 keV. Among the emission lines from abundant elements in AGN spectra, the most prominent is the Fe K α line at 6.4 keV. The line can be subject to Doppler and gravitational effects that can cause skewed line profiles and photon energy shifts. These spectral features, including the skewed line profile and the Compton hump, have been used in the by the *NuSTAR* mission to derive constraints on spin values. Moderately spinning black holes are currently under-explored as current spin measurements are biased toward high-spin values [e.g. 1, 2]. In fact, many sources having spin values in the range a = 0.4–0.7 have upper limits compatible with much higher spins. Lower spins have not been measured yet, even though low and moderate spins are deemed to be associated to extreme mass values of the order of $10^8 M_\odot$ or greater.

Mrk 876 is an optically selected Seyfert type-I AGN from the Palomar-Green (PG) Bright Quasar survey [3] being often also referred to as PG 1613+658. At X-ray energies the source has been detected by *Ginga* [4] and later also at even higher energies in the combined *Swift – INTEGRAL* X-ray (SIX) survey [5]. Successively also the survey of *Swift* alone [6] has detected the source, while Mrk 876 is not detected in the survey of *INTEGRAL*. *Swift*/XRT follow-up observations suggest the source hosts a spinning SMBH measured through a transient gravitationally redshifted Fe line [7].

Here we present the analyses of the *NuSTAR* observation on Oct. 22nd, 2020 of Mrk 876 [8] with the aim of characterizing its emission mechanism through its broadband spectrum. The redshift of Mrk 876 z = 0.1385 [9] corresponds to 551.4 Mpc for H_0 = 73 km s^{-1} Mpc^{-1} assuming Hubble flow that we do throughout this paper.

2. Mrk 876: spin analysis

Mrk 876 has been observed by *NuSTAR* for 30 ksec on Oct. 22nd, 2020 (obs id: 60160633002). The absence of variability in both detector modules (FPMA, FPMB) allowed for the use of the photons of the entire observation time for the spectral analysis. This analysis shows that an absorbed (fixed to the Galactic value) power-law model cannot reproduce the data resulting in a reduced chi square $\chi^2{}_{red}$=1.15. The residuals of this fit are shown in Figure 1: the green horizontal line represents the absorbed power-law model, while the data display large residuals at energies 4-6 keV and at energies above 10 keV, which are typical reflection features. Additional absorption with respect to the Galactic value is not needed nor has any variability of the absorption been observed by many independent observations [7]. This is not surprising as Mrk 876 is a Seyfert type-1 AGN, which allows for a rather unobscured view onto the accretion region. The best fit model is an absorbed (fixed to the Galactic value) broken power-law model plus a gaussian component (`wabs(bknpower+gauss)`) for which the former and the latter mimic the Compton hump and the large excess at energies 46 keV, respectively. This excess at low energies is broad having a width of σ = 1.4 keV.

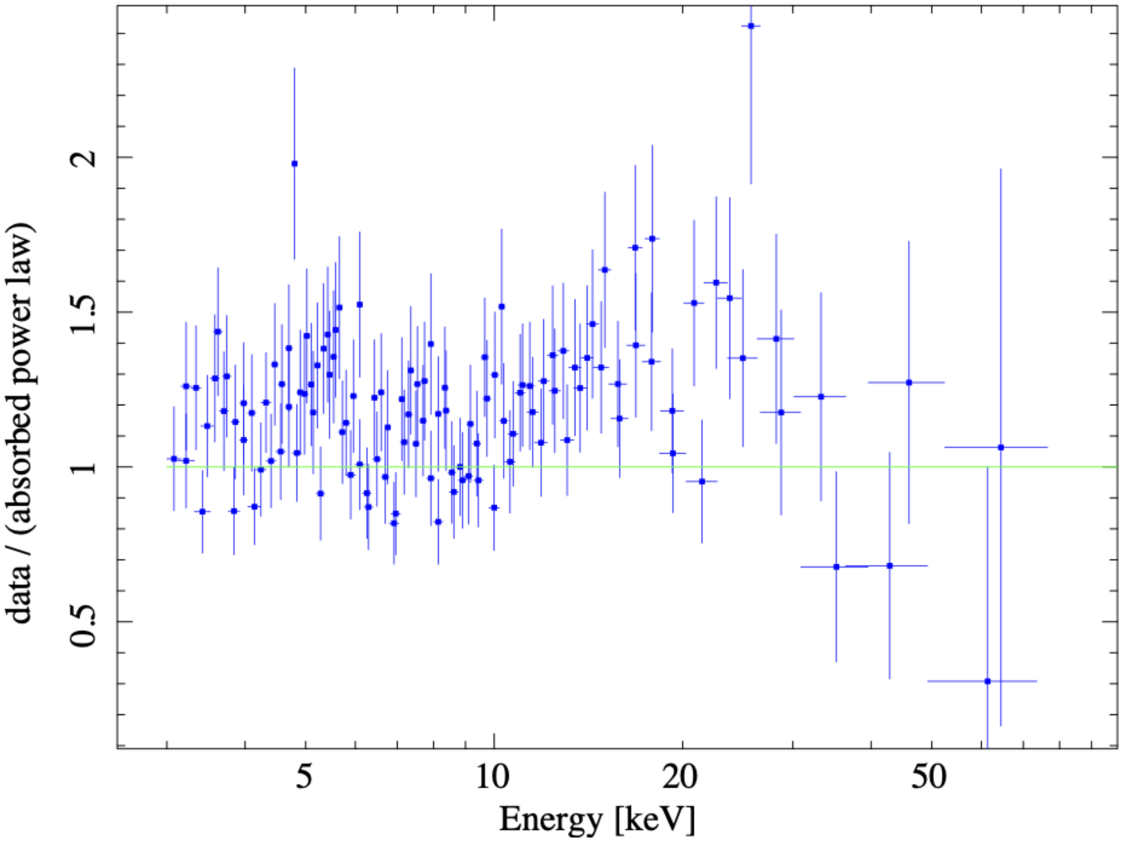

Figure 1: Residuals resulting from the fit of the *NuSTAR* data with and absorbed power-law model (green horizontal line). Excesses can be seen at energy above 10 keV and between ~4–6 keV)

To fit the distant (from the accretion disk) reflection scenario we used the Galactic absorption for each model. The fit with (`cutoffpl+xillver`) cannot constrain the inclination angle i. Additionally, the cut-off energy E_{cutoff} =11.5 keV is much lower than typical values. Also the less sophisticated model (`cutoff+gauss`) is not able to properly fit the spectrum resulting in a $\chi^2{}_{red}$=1.2. A similar result is found for the (`cutoff+pexmon`) that is also unable to constrain the inclination angle. For an alternative scenario, also the warm absorber hypothesis is explored even though the spectra of Mrk 876 do not exhibit strong absorption edges. This scenario is tested with the (`bknpower+zxipcf`) that mimics partially ionized absorbing matter that intercepts the primary continuum along the line of sight. Despite resulting in a good fit (not the best though) of $\chi^2{}_{red}$=1.05, the inferred parameters are physically unsatisfactory being the ionization parameter log(ξ)=3.0 erg s^{-1} and the column density N_H=10^{24} cm^{-2} that are inconsistent with typical values of log(ξ)=0–2 erg s^{1} and N_H ~ 10^{20}–10^{22} cm^{2} [e.g. 10]. Additionally, absorbing matter of N_H=10^{24} cm^{-2} intercepting the line of sight would cause variability of the absorption parameter that however has never been observed in the many available observations by XMM-*Newton* and Swift/XRT [7].

These evidences disfavor the distant reflection scenario, which is also reinforced by the fact that such a scenario would produce a rather narrow Fe-line, in contrast with the broad excess measured by *NuSTAR*.
In the reflection scenario off the accretion disk the relativistic effects lead to a broad excess at energies of the Fe-line being the result of strong Doppler and gravitational shifts and the gravitational redshift. These effects are convolved with the rest-frame X-ray reflection in the widely used self-consistent model RELXILL, which is able to properly reproduce the skewed low-energy spectral excess and the Compton hump for Mrk 876 [8]. During the fit all the parameters are free to vary and the fit returns a rather good statistical result of $\chi^2{}_{red}$ = 0.97. The inferred Fe abundance A_{Fe}=1.85 (+2.36/-1.24) is nearly twice the solar value, while the reflection fraction is 1.91 (+17.54/-1.13). For the ionization state an upper limit of $\log(\xi) < 3.17$ is obtained. While the inner radius of the accretion disk remains unconstrained, the outer radius is 400 gravitational radii. The inferred emissivity index is q=4.56 (+0.70/-0.98) and for the spin an upper limit of $a < 0.85$ is derived. The inferred inclination angle is i=32.84°(+12.22/-8.99), which is in agreement within the errors with an independent measurement of i=15.4° (+12.2/-6.8) by [11]. The spinning black hole is in agreement with very recent and sophisticated reverberation mapping probes that result in non-physical parameters for a Schwarzschild black hole [12].

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